

FABRICATION OF ALIGNED CONVEX CNT FIELD EMISSION TRIODE BY MPCVD

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Abstract

In this work, vertically aligned carbon nanotubes (CNTs) were used to form a microcathode with a convex surface profile, being selectively synthesized from Microwave Plasma Chemical Vapor Deposition (MPCVD) with Ni or Co as catalysts. A single-mask micro-fabrication process achieved an array of 10 μm square CNT microtriodes with self-aligned gate. This convex profile is important in preventing cathode-gate leakage without resorting to more complicated fabrication processes or utilizing a gate over-etched approach. The dc characteristics of the CNT triode in a common emitter configuration were investigated, including dc parameters such as transconductance (g_m), amplification factor (μ), and anode resistance (r_a). The transconductance of a field emission triode establishes the current driving capability while the amplification factor determines the ultimate voltage gain of the amplifier. The triode device demonstrated good gate-controlled modulation of the emission current with distinct cutoff, linear and saturation regions of operation. A gate turn-on voltage as low as 25 V has been achieved. A large amplification factor of ~ 352 and transconductance of $\sim 2 \mu\text{S}$ are obtained. These transistor characteristics are substantially improved compared to our previously reported results [1].

INTRODUCTION

Previously, we successfully fabricated a CNT triode with a gate turn-on voltage of ~ 40 V by thermal CVD [1]. Since the CNTs grown were randomly oriented, an over-etched gate structure [1] was adopted in order to avoid cathode-gate leakage problems. As a result, the large cathode-gate spacing led to high gate turn-on voltage and triode characteristics of $\mu = 10$ and $g_m = 47 \text{ nS}$ when configured as an amplifier. In order to overcome gate leakage which limits performance of the CNT triode, three approaches have been reported in literatures: (i) over-etched gate electrode or reduced gate overhang [1,2], (ii) sidewall protector [3,4], and (iii) post-growth processing which includes utilizing chemical mechanical polishing (CMP) technique [5], and plasma trimming of the grown CNTs [6]. In this work, an alternative approach with gated convex CNT cathodes was applied to minimize the cathode-gate leakage problems.

EXPERIMENTAL

Vertically aligned convex CNT microcathodes were synthesized selectively inside a triode mold utilizing MPCVD method. A thin layer of Ni or Co and Ti was sputter-deposited as the growth catalyst and diffusion barrier, respectively. The surplus catalyst on the polysilicon gate was removed by photoresist lift-off technique. A hydrogen plasma pretreatment of the catalysts was performed. The CNTs synthesis was at 20 Torr, microwave power 1.0 kW and substrate temperature 650°C. Methane (CH_4) diluted in hydrogen (H_2) was the carbon source. The growth time of the CNTs was ~ 60 to 90s, critical to obtain the right height of the vertically aligned CNT cathodes. In device characterization, the CNT triode was tested in common emitter amplifier configuration for dc field emission characteristics. The measurements were performed at room temperature in a vacuum chamber evacuated to a base pressure of 10^{-6} Torr. Measurements of the anode emission current, I_a as a function of the anode voltages (V_a) for different gate voltage (V_g) were collected.

RESULTS AND DISCUSSIONS

The single-mask micro-fabrication process achieved an array of 10 μm square CNT microtriode, as depicted in Figure 1. Vertically aligned CNTs with diameters ranging from 20-30 nm were grown. The H_2 plasma pretreatment of the sputtered catalysts was utilized to achieve gated CNT cathode with convex profile or shorter nanotubes on the edges, Figure 1. This convex profile is important in preventing cathode-gate leakage without resorting to complicating fabrication processes such as sidewall protector or gate over-etching that result in higher turn-on voltage. The cathode-gate spacing was $\sim 2.0 \mu\text{m}$. Gate turn-on voltage as low as 25 V has been achieved and the emission current follows Fowler-Nordheim electron tunneling behavior, Figure 2. When tested in a common emitter configuration, the CNT triode device demonstrated good gate-controlled modulation of the emission current with

distinct cutoff, linear and saturation regions of operation. A large dc gain or amplification factor of ~ 352 at $I_a = 1.7 \mu\text{A}$, and transconductance of $\sim 2 \mu\text{S}$ at $V_a = 400 \text{ V}$ are obtained. These transistor characteristics are substantially improved compared to our previously reported results [1], where randomly oriented CNTs were grown by thermal CVD inside an over-etched gate triode mold. The improvement is attributed to the vertically aligned CNTs with convex profile, smaller cathode-gate gap and larger array size.

CONCLUSION

Vertically aligned CNT field emission triode fabricated with a single-mask process and catalyzed MPCVD, configured as an amplifier has demonstrated very good dc characteristics with high dc gain and transconductance at low operating voltages. The vertically aligned CNT triode with a convex profile performs better than the triode grown with thermal CVD method [1]. This CNT triode amplifier could be a candidate for high power, high gain and high frequency amplifier applications that requires radiation-hardness and temperature-immune capability.

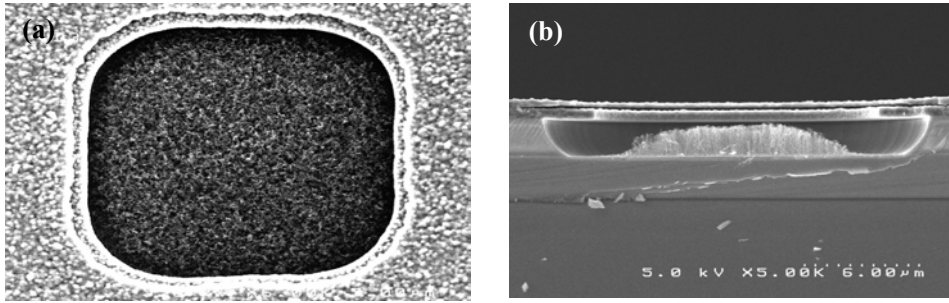


Figure 1. SEM micrograph of the aligned CNT triode (a) oblique view, and (b) cross-sectional view.

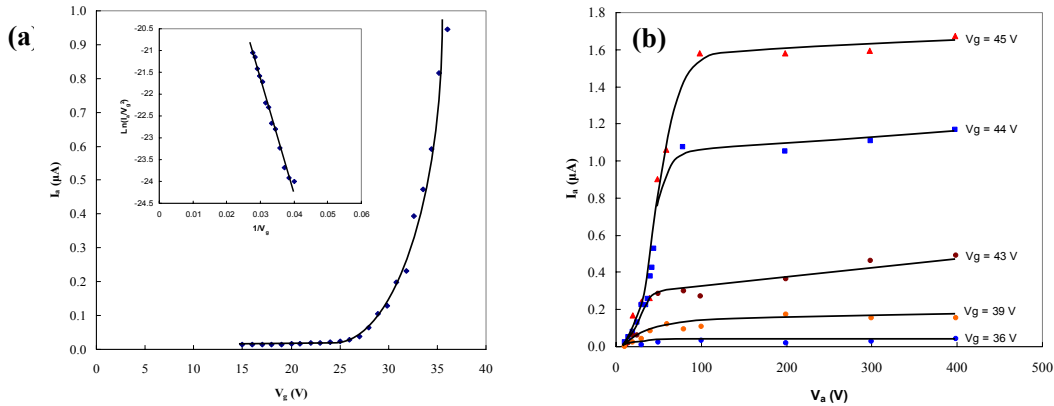


Figure 2. (a) Plot of the measured anode currents, I_a vs. the gate voltage, V_g , and (b) Plot of I_a vs. the anode voltage, V_a for different V_g of the CNT triode.

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